Reference Manual

For Apex version 2.2

Michael Freed
Eric Dahlman
Michael Dalal
Robert Harris

NASA Ames Research Center, 2002

Contents

1.0 Introduction

1.1 What is Apex?

Apex is computer program for generating adaptive, intelligent behavior in complex environments. It is the principle element of the Apex System which includes a range of components for modeling, simulating and analyzing human behavior. Intended uses include:

- helping engineers evaluate and design human-machine systems
- anticipating how newly introduced technologies will affect human operators
- standing in for human participants in a training simulation
- exploring or illustrating scientific theories of human performance

The Apex approach to human modeling separates aspects of behavior and performance that apply to intelligent agents in general from aspects that are particular to humans. The Action Selection Architecture (ASA) integrates AI techniques such as hierarchical planning and online-scheduling seen as useful for creating agents with human-level ability. By building capabilities into the architecture and providing a high-level language for behavior representation, Apex makes it easier to create human agent models for complex task environments. Findings from cognitive psychology and other areas concerned with human performance are incorporated into the Human Resource Architecture (HRA) which parameterizes and constrains the general agent model. A human model in Apex combines the ASA and HRA with a set of behavior representations, some specific to the task at hand, others general across many tasks.

Apex is meant to be a practical tool. It has proven successful in automating a Human-Computer Interaction analysis method called GOMS, including an especially powerful but complex variant called CPM-GOMS. The approach has also been useful for rapidly developing simulations of normative human behavior and for reconstructing incidents involving human error.

As a practical tool, one crucial consideration is to minimize the time and expertise required to build new models. This goal influences every aspect of Apex. For example, in production-system based cognitive architectures, behaviors are represented at an "atomic" level at which the mechanisms of cognitive processing can be described in detail. In Apex, behavior is represented at a high-level, allowing modelers to ignore how behavior is generated and focus on what behaviors are desired. This can be viewed as trading usefulness at representing scientific theories of cognition for usefulness at representing complex, large-scale tasks. Similarly, Apex incorporates approaches to many high-level aspects of cognition such as selecting action under uncertainty, managing concurrent tasks, and task interleaving. These capabilities are relatively easy to invoke though a modeler is provided little flexibility in representing how they are realized.

In developing Apex, it has become clear that constructing a practical, broadly applicable human-system modeling tool is too great a job for any small team of individuals. Given the great number of issues to be addressed and the many different kinds of expertise needed, such an endeavor is most naturally carried out through a

distributed development process. The design of the Apex system lends itself to distributed development. While the action selection architecture is complex and its subcomponents tightly coupled, the other elements of the system are modular and thus relatively easy to extend, modify or replace. For example, cognitive, perceptual and motor faculties represented in the resource architecture are completely independent of the core action-selection mechanism, allowing modelers to "plug-in" alternative sub-models. Similarly, Apex includes a set of reusable “building blocks” for new models that can easily be modified or added to. This document is intended mainly to support the use of Apex in its current form but also provides important information for developing new Apex elements.

1.2 System Components

Software components of the Apex system fall into four categories or component layers including: the intelligent agent layer, the human/environment layer, the infrastructure layer and the user layer. The intelligent agent layer provides the ability to specify simulation entities with complex behavior reflecting goals, new events and “how to” knowledge. Its primary use in APEX is to model human operators, although it is also useful for modeling other simulation entities such as robots and aircraft autopilots. The intelligent agent layer currently includes a single component: the Action Selection Architecture (ASA), an import from the field of artificial intelligence originally designed to control mobile robots acting in complex, real-world environments. The capabilities it provides facilitate simulation of relatively sophisticated aspects of human behavior such as adapting to time-pressure, coping with uncertainty, and interleaving multiple tasks.

The human/environment layer includes a wide range of components for specifying and making inferences about humans and other entities that populate a simulation. An important subset of these components are human resources models – representations of human cognitive, perceptual and motor faculties such as hands and eyes – which together comprise the Human Resource Architecture (HRA). Each resource model specifies performance-limiting characteristics. For example, the vision model specifies a restricted field of view, variable acuity, and a time lag between sensing and interpreting visual information. The agent and resource architectures combine to model a human agent. While the action selection architecture provides the ability to engage in complex behavior, the resource architecture causes this behavior to conform to human limits.

Also included in the human/environment layer are means for representing and reasoning about physical spaces (locales) and the spatial (e.g. containment, attachment, adjacency) and visual properties (e.g. color, orientation) of objects in a locale. Other components in this layer are building blocks for constructing models in human-computer interaction domains. These include representations of interface widgets (e.g. buttons, mice, keyboards) and of behaviors for using those widgets. The common theme for the components of this layer is that they are ingredients for building models of human-machine systems. Though intended to be reusable, they should not be considered core components of the Apex system. Users are encouraged to extend or replace these elements as they see fit.

The infrastructure layer provides essential services including simulation, trace event logging and mechanisms for interoperating with non-Apex processes such as an external simulation of a physical environment. The simulation component is composed of three parts: a simple language for defining "objects" to be simulated, a simulation engine whose job it is to carry out the actual simulation process, and a Lisp interface for controlling the simulation process. Some extensions to the Apex system, including development of new human resource models, require familiarity with simulation mechanisms and other components of the infrastructure layer. However, most users will probably need to know little more than how to operate the simulation engine – e.g. to begin or pause a simulation trial.

The user interface layer provides components to facilitate model construction, model debugging, and analysis and visualization of simulation output. The central element of this layer is Sherpa, a GUI that provides a range of services including buttons (shortcuts) for controlling the simulation engine, tools for handling large volumes of trace output, tools for examining simulation entities during and after a run, and a facility for automatically generating graphical representations of agent behavior.

To apply Apex in a particular domain, a user creates a simworld – a representation of a particular task and task environment. For example, to simulate people using a new automatic banking machine, an APEX user would represent the new machine's appearance and behavior, the procedural knowledge needed to operate it, and a scenario providing specifications for a particular simulation run. Together, the APEX system and user-defined simworld elements constitute an APEX application. To develop new applications, a user should be comfortable programming in LISP and should become familiar with the contents of this manual.

1.3 Getting More Information

This document focuses on the practical aspects of using Apex. For the current version, see ftp://eos.arc.nasa.gov/outgoing/apex/apex/. More information is available from several sources:

Published papers describe many aspects of Apex including: using Apex for CPM-GOMS (John, et al. 2002) and GOMS (Freed and Remington, 2000) analyses; human error prediction (Freed and Remington, 1998); human-system modeling methodology (Freed and Remington 2000b; Freed, Shafto and Remington 1998; Freed and Shafto 1997); and multitask management (Freed 2000; Freed 1998a).

Apex-related papers and other information can be found on an experimental website: http://human-factors.arc.nasa.gov/apex/www/apex/

For the most detailed available description of the Apex action selection architecture and the modeling approach it supports, see (Freed 1998b).

To report a bug or consult on a technical problem, contact the Apex development team (apexhelp@eos.arc.nasa.gov). For information related to the development of the Apex system send email to mfreed@arc.nasa.gov.

Extending and modeling in Apex may require programming in Common Lisp. The complete text of Common Lisp by Guy Steele can be found at:
http://www-2.cs.cmu.edu/afs/cs.cmu.edu/project/ai-repository/ai/html/cltl/cltl2.html

2.0 Getting Started

2.1. Setting up

To use Apex you'll need the following software:

1. The Apex system

Using a standard web browser, Apex can be downloaded from the following ftp site along with installation instructions (see the file README).

ftp://eos.arc.nasa.gov/outgoing/apex/apex/

2. Java Runtime Environment (JRE)

This is most likely already installed on your computer. If needed, the JRE may be obtained from the Apex web site along with installation instructions (see the file README).

3. Common Lisp system

Apex currently runs in different versions of Lisp. In some versions, you must install Lisp as a separate step; in others Apex and Lisp are combined and downloaded as a single file. Which is appropriate will vary depending on your platform and the current distribution. The Apex installation instructions clarify this requirement.

4. Text editor

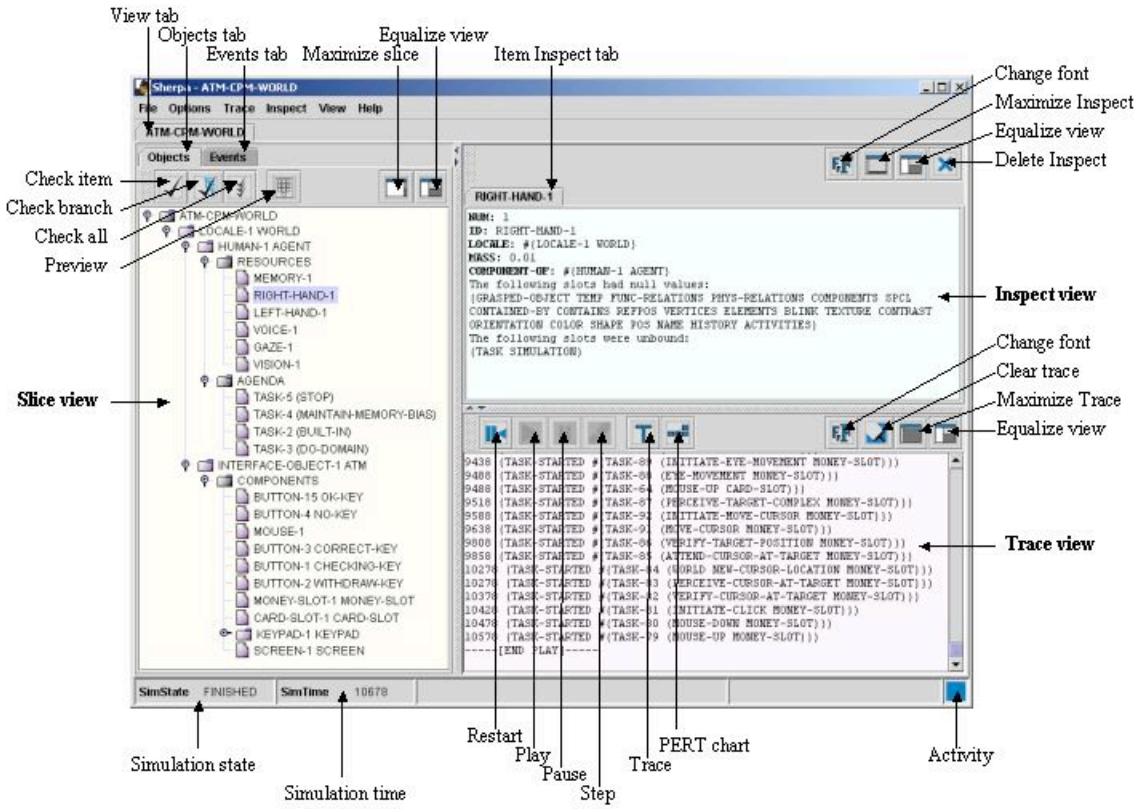
Using Apex requires programming in Common Lisp. The most popular editor for this is Emacs, which is freely available for all platforms on which Apex runs. Emacs itself has a few variations, including Emacs-like editors such as Fred (built in to Macintosh Common Lisp) and Alpha (shareware). Any other text editor may also be used.

2.2 Quick Tour

This section briefly steps you through some of most basic operations in using Apex via Sherpa, its graphical user interface. Using the attached Sherpa diagrams as a reference, follow these instructions to load, run, and inspect the results of a sample scenario modeling a person operating a modeled automatic teller machine (ATM).

1. Start Apex

Directions for how to start and exit Apex, which vary depending upon the distribution, are found in the Apex installation instructions. Using the method appropriate for your Apex distribution start Apex and its graphical user interface, Sherpa.



2. Load a Simworld

a) Click the Play button in Sherpa. This "connects" Sherpa to the Apex system (which runs as a separate application). The button will be replaced by a drop-down menu containing sample simworld names.

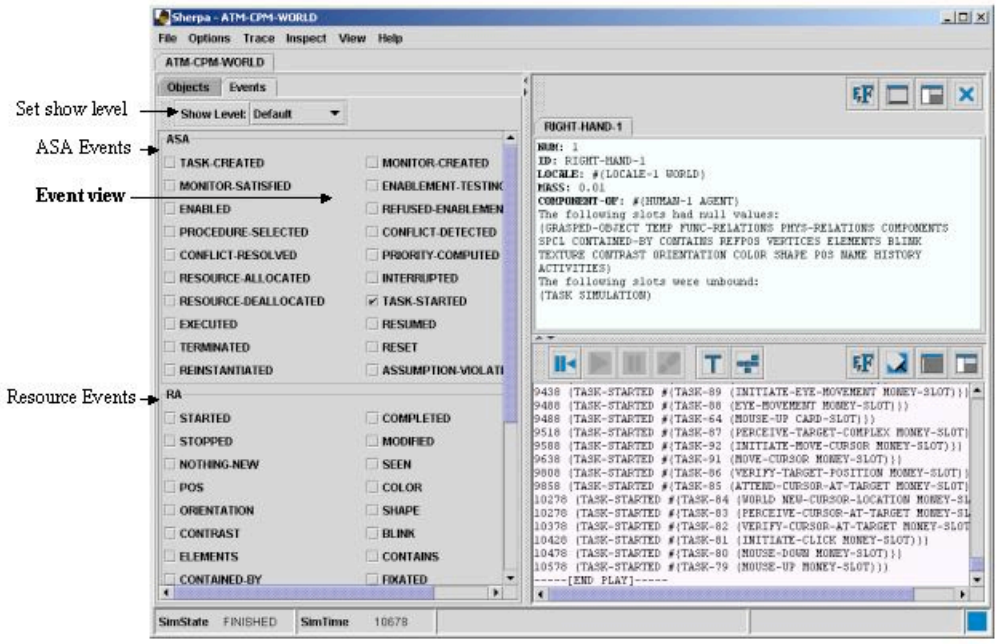
b) Select a Simworld. Select the simworld ATM-CPM-WORLD from the drop-down menu. This *loads* the simworld into Apex. Sherpa's screen will change to reveal the simulation control and viewing interface.

3. Run the Simulation

Press the *Play* button. Events will print in the *Trace view* as the simulation runs.

4. Inspect Objects

The *Slice view* lists the scenario objects in a collapsible hierarchical fashion. Click on the "lever" icons to expand objects. Double click on objects to display information about them in *Inspect view*.



5. View the PERT Chart

Click on the *PERT chart button* to generate a PERT chart for the simulation run. Inspect the chart and experiment with its manipulation controls.

Note that the PERT chart window has become the top *View tab*. To bring up the simulation control interface, click on the ATM-CPM-WORLD View tab.

6. Change Trace settings

Click on the *Events tab* to access the *Event view.* By default, only a small fraction of the trace data produced during simulation is shown. To see more, click on the *Set show level* drop-down menu and select *asa-low*, then click the *Trace* button to show a new (larger) subset of the events generated in the previous simulation run. See section 3.5.1 for more on controlling trace display.

3.0 Using Apex

3.1 Interacting with Apex

Users interact with Apex mainly through three interface elements: a standard text editor such as Emacs; Apex's graphical user interface, Sherpa; and a Lisp interactive window, known as a listener. In most cases, a user will wish to have all three of these elements available when building and running Apex models.

A text editor is needed to create and modify Apex applications. Apex applications are written in the Common Lisp programming language, for which the most popular editor is Emacs. Emacs "understands" Lisp better than any other editor (being itself largely written in Lisp) and provides a large and customizable set of programming conveniences. However, any text editor is acceptable. Alternatives to Emacs include Fred (built into MCL) and Alpha (Mac) which have Emacs-like features, vi (built into Unix).

Sherpa is used to start Apex simulation runs, examine simulation elements, and to generate, format and display simulation output. It is possible to use Apex without using Sherpa. However, Sherpa provides the only means for obtaining graphical output from a simulation (e.g. PERT charts, object trees) and for pausing a simulation run interactively.

The Lisp listener (or simply *listener*) is a text window always present when Apex is running. Listeners are inherent to Common Lisp systems and provide an interface for evaluating Lisp expressions. Interacting through the listener can be especially valuable when debugging Lisp code. Depending upon platform, there may be one or more listeners present while Apex is running. A listener may also be used as a primary means of interacting with Apex[1]. This can be done in two ways. A user can invoke Lisp functions directly using functions described below (e.g. `(startsim)`). Alternately, a prompt-driven interface can be invoked by entering

```
(apex)
```

in the listener. This provides access to all the features of Apex, except for the graphical features of Sherpa. The prompt-driven interface is still in development; user feedback is especially encouraged.

Listeners also display debugging information and other messages while Apex runs. Most of what is normally displayed is internal information that can be ignored. However, if an error occurs, the Apex run is interrupted and a debugging prompt appears, accompanied by an error message. Such occurrences are most frequent during development or modification of a model and are usually caused by Lisp programming errors.

[1] **Warning**: using the listener to interact with Apex while also using Sherpa may lead to unexpected behavior – only one means should be used in an Apex session.

3.2 Loading a model

A model is also called a *simworld* (simulation world). Using Sherpa, select Simworld from the File menu to see another menu of available simworlds. Or, if the Sherpa window has just appeared or Sherpa has been reset, pressing the Start button replaces this button with a drop-down menu of simworlds. A simworld begins loading when the mouse is released. This may take 10-20 seconds.

To load a simworld directly from Lisp, use the function *load-simworld*. For example, the following loads a simworld called *atm-world*.

```
(load-simworld 'atm-world)
```

3.3 Running Simulations

3.3.1 Starting a simulation run

Once a simworld is loaded, the simulation may be run by clicking Sherpa's Play button. Alternately, the Lisp command *(startsim)* may be used. This function is also used to resume after a pause. To force the simulation to start at the beginning, use *(restartsim)*. The simulation will run until completion or until a scheduled pause point arrives.

3.3.2 Pausing and resuming a run

T o pause a simulation run interactively (while the simulation is ongoing), click the Pause button[2]. Alternately, a user can program (preset) a pause from the Lisp Listener. This is especially useful for model debugging. Four different pause presets are supported:

Scheduled pause: A pause may be scheduled for a specified simulation clock time. The time may be specified before the simulation is run, or during a pause, if the (new) scheduled pause time is greater than the current time. Pauses are scheduled by typing the following in the listener:

```
(set-pause-time N)
```

where N is an integer specification of the time in simulation time units (milliseconds by default).

Cyclic pause: A simulation pause can be scheduled to occur once every N simulation events (events in the simulation engine's internal activity queue). This is useful for coping with infinite loop bugs which can occur within a given simulation "moment," making it unhelpful to pause at a scheduled time that will never be reached. Such pauses are scheduled by typing the following into the listener:

```
(set-pause-cycle N)
```

[2] The pause button is not supported on all platforms, due to lack of proper multithreading support in some Lisp implmentations.

where N is an integer specifying the number of events.

After initialization: The simulation may be paused immediately after a simulation trial has been initialized using the form:

(pause-after-init <flag>)

where <flag> is either T (true) or nil (false). This is useful for determining whether a bug occurs before or after initialization is compelte.

After each trial: The Apex simulation engine supports multitrial simulation runs. The simulation may be paused at the completion of each trial using the form:

(pause-after-trial <flag>)

where <flag> is either T (true) or nil (false).

Pauses may be specified non-interactively (i.e in code) by inserting the forms given above forms in your Lisp simworld code, most commonly in the initialize.lisp file.

3.3.3 Resetting the Simulation

Resetting a simulation means restoring it to its starting state. This may be done after a run is complete or during a pause. Click the Reset button in Sherpa. In Lisp, use *(resetsim)*.

3.3.4 Single-stepping.

It is possible to advance a simulation one step, or activity processing cycle, at a time. Single steps may be taken when the simulation is reset or whenever it is paused. Attempting to single step when the simulation is finished will have no effect. Click the Step button in Sherpa. In Lisp, use *(stepsim)*.

3.4 Creating new models

3.4.1 Simworlds

Models in Apex are called simworlds because they include not only human agents and their cognitive/behavioral representations, but also models of the physical environment. To build a simworld, one creates three files with the following filenames:

1. initialize.lisp (specifies one or more simulation scenarios)
2. pdl.lisp (specifies "how-to" knowledge)
3. definitions.lisp (specifies properties of objects in the task environment)

The initialize file contains specifies the scenario to simulated. This includes the initial state of every object in the simulation including human agents and their behavior representations. Also included are any parameters that determine how events unfold over the course of the simulation such as the probabilistic values for unusual events. Information on constructing an initialization (scenario) file is provided in 3.4.2. The pdl file describes how-to knowledge notated in Procedure Description Language (see section 4) used by any human agent in the simulation. The definitions file contains any Lisp code needed to support the scenario. This will typically include class and method definitions for physical object types specific to the scenario's domain. For example, in a commercial jet scenario, the definition file might include definitions related to aircraft flight behavior and cockpit controls.

The simworld files must reside in the same directory (folder) as one another, but this directory may be filed anywhere. It is strongly advisable to file it outside the Apex installation directory, so that your work is not accidentally overwritten when installing a new version of Apex. These files do not have to contain all (or indeed any) of the information directly, but may instead load other files as needed.

3.4.2 Specifying a scenario

A scenario file specifies everything the generic simulation engine needs to know for a simulation run. This should include: a set of entities (including humans) to be simulated; the initial states and initial behaviors of those entities; setting for parameters that affect how the simulation unfolds but are stored external to simulation entities (e.g. a global variable representing the probability of some unusual occurrence). Initialization is performed by a simulation engine method called *initialize-simulation*. The following internal organization is recommended (see apex/app/examples/<*simworld*>/intialize.lisp) for examples):

```
(initialize-simulation
  <specify-simulation-parameters>
  <init-external-datastores>
  <init-state-toplevel-objects>
  <assemble-toplevel-objects>
  <link-toplevel objects>
  <init-behavior-toplevel-objects>)
```

The first two elements will not normally be needed. Simulation parameters include scheduled pauses (3.3.2) and the number of simulation trials to be run (1 trial by default). External datastores refer to entities created prior to initializing the simulation that contain information used by simulation objects; initialization is required if stored information can vary, especially as a result of write actions by simulation entities.

Toplevel objects are the primary entities to be simulated. These often "contain" other simulation entities which are considered parts, rather than toplevel. For example, the data structure representing a human contains resource modules representing a left hand, a right hand, voice, etc… During initialization, toplevel objects are created and

given initial state values. Assemble methods specific to the class of object just created are then used to automatically create and initialize parts. Apex includes a definition for the class *standard-human* and an assemble method that creates resource parts for it. Classes and assembly methods defining non-human entities such as keypads, mice and automatic teller machines can be found in example simworlds. New definitions should be declared in the simworld's definitions.lisp file.

After objects are created and their initial state set, functional linkages between objects should be established. For example, after creating a switch and a lamp as individual objects, the two can be linked to represent that the switch controls the lamp. Such information is usually stored just as state attributes are stored – i.e. in slots specified in the class definition. Thus, the definition of a lamp class might include the slots *illuminated* to represent whether it is on or off, *working* to represent whether it is working or malfunctioning, and the link slot *controlled-by* which points to the object that determines whether it is powered on.

Finally, behaviors of instantiated objects can be initialized. This has to come last because the specification of behavior often requires knowing its state and links. For instance, the method start-activity might be used to cause the lightswitch to itself glow whenever the lamp is off (making it easier to find in the dark) but in working order. The method representing this behavior needs to check the state values of the switch and the lamp to determine correct initial behavior.

3.4.3 Specifying agent knowledge

Agent knowledge is specified in the file pdl.lisp using the PDL notation described in section 4. A complete PDL specification requires:

- a top-level PDL procedure with an index clause of the form *(index (do-domain))*. This is used to initialize agent behavior.
- a PDL procedure corresponding to every step in the do-domain procedure and every step in these new procedures other than steps specifying primitive actions

3.4.4 Specifying new agent resources

In an Apex human model, the general action selection architecture does not interact with the world model directly. Instead, perceptual, cognitive and motor resources comprising a resource architecture mediate interactions with the world and also constrain the agent to perform with human limits and other characteristics. Resources are implemented as software modules and may be replaced or modified with moderate effort[3]. This section describes how to create a new resource, e.g. a prehensile tail. Users interested in creating or modifying resources should look at examples in apex/app/building-blocks/human.

[3] It not always necessary to define new resources to get some of the functionality one might want. If the only need for a resource is to affect the agent's resource allocation, it is enough to simply name the resource in a profile clause (making it a virtual resource). The action selection architecture will do resource conflict detection and resolution without regard for whether that resource is associated with a class definition.

Step 1: Define the new resource type

Every resource is implemented as Lisp class with slots representing resource state attributes. The following defines a class of resources called *tail* with a single state attribute called grasp. The value of this slot is a representation of an object that the tail is currently grasping – or nil if no such object exists.

```
(defclass tail (human-resource physob)
  ((grasp :accessor grasp :initarg :grasp :initform nil)))
```

Tail inherits from the classes *human-resource* and *physob* (which itself inherits from *visob* – see appendix B) which carry along a number of state attributes. Users are encouraged to study the definitions of these objects. New resource classes associated with a particular model can be stored in a simworld definitions file.

Step 2. Redefine the class standard-human to include the new resource

Human models in Apex are instances of the class *standard-human*. As there is currently no support for human models based on other classes, *standard-human* and associated functions must be modified to make use of new resource types. This class is defined in apex/app/building-blocks/human/human.lisp The first required modification is to the class definition itself, adding a slot named for the new resource.

```
(tail :accessor tail :initarg :tail)
```

Next modify the *assemble* method defined in the same file to include a call to the function add-apex-resource.

```
(add-apex-resource (make-instance ‘tail) human-1)
```

In some cases, it is useful to create active resources – i.e. resource that engage in some periodic behavior rather than passively accepting commands from the action selection architecture. Such behaviors can be initialized in the assemble method. For example, the following line will initiate a wiggle action every 1000 simulation time units (1 unit = 1ms by default). This assumes that the method *wiggle* has been defined and, when called, produces an appropriate effect.

```
(start-activity human-1 ‘wiggle :resource (tail human-1) :update-interval 1000)
```

Step 3: If appropriate, define activities the new resource can be commanded to carry out

Resources representing motor faculties (e.g. hands, tails) can be commanded to action by the PDL primitive action type *start-activity.* Each new kind of action (activity) is represented by a class (used to represent the state of the action at a given moment) and

one or more methods defining the effect(s) of the activity. There are two kinds of methods: complete-activity and update-activity. The former is used to describe what happens when the activity comes to completion. The latter describes what happens at intervals prior to completion. The following definitions support the activity *tail-grasp*.[4]

```
(defclass tail-grasp (resource-activity)
  ((target :accessor target :initarg :target :initform nil)))

(defmethod complete-activity ((act tail-grasp) (tail-1 tail) &key cause)
  (signal-event (grasped (target act) (setting act) :cause cause))

(defmethod grasped ((obj physob) (tail-1 tail) &key cause)
  (setx (grasp tail-1) obj :cause cause))
```

A step from such as the following can be used to invoke this behavior from PDL:

```
(step s1 (start-activity tail tail-grasp :target banana :duration 2500))
```

Step 4: If appropriate, define event-generating processes invoked by the resource

Some resources, particularly those modeling perception, generate input to the action selection architecture called cogevents. This is accomplished using the function cogevent

```
(cogevent <eventform> <agent> [:trigger-asa <Boolean>])
```

where <eventform> is an arbitrary list representing what has occurred and <agent> is a pointer to the (human) agent that has detected the event. The optional trigger parameter determines whether the event should be processed by the action selection architecture immediately or whether it should be stored in a buffer and processed the next time a processing cycle for the architecture occurs.[5]

3.4.5 Registering a new simworld

Apex can correctly load a simworld only if that simworld has been named and registered. Registration is accomplished by entering the following Lisp form:

```
(defsimworld <simworld-name> <directory>)
```

where simworld-name is a symbol *without* a quote and directory is a string describing where the simworld files are located in your directory structure. Example:

---

[4] Signal-event and setx are special forms used to track causal dependencies in a simulation. The former should be wrapped around a function or method call implementing a change of state to one or more simulated objects. Setx should be used to effect the state change as it were setf.

[5] There is no automatic architecture cycle; it must be triggered by a resource. In the default model, the vision resource triggers processing periodically.

(defsimworld my-atm-world “Macintosh HD:Apex Worlds:my-atm-world”)
(defsimworld my-atm "/home3/smith/simworlds/my-atm-world")

The first example uses Macintosh pathname format and the second, Unix (Linux). Use the correct syntax for your platform. Also note that the simworld name and its directory name need not be identical, allowing the directory to abbreviate.
The defsimworld form may be typed into the listener, but Sherpa will then need to be reset (if it has already been started). To avoid the inconvenience of having to enter this form in every session, one can put all defsimworld forms in the file apex/app/examples/allworlds.lisp, which is loaded whenever Apex is started.

3.5 Managing Simulation output

All events that occur during a simulation trial are recorded in an event history or **trace**. Trace information is displayed as textual data with each line specifying a timestamp and description of a single simulation event. The trace may be viewed as the simulation runs (i.e. as the events occur), after the run is complete, or during a pause. To cause a trace to be displayed after a run (possibly with new filter settings – see below), press the Print-Trace button above Sherpa’s trace view pane (it looks like a T). From Lisp, type *(generate-trace)*.

3.5.4 Filtering raw trace data

A simulation trace may be viewed in its entirety, but this is usually too much information to be useful. It is possible to specify filter criteria that limit the displayed trace information. Filter effects apply whether the trace is viewed at runtime or afterwards. Events are most often filtered based on event-type. The first element of an event description determines its type. For example, the types of the two example events below are *task-started* and *suspended*.

(task-started #{task-21 (fly-to-waypoint)}
(suspended #{task-19 (push-button-1)}

There are three basic ways to filter event traces:

1. The first is to specify a *show level.* A show level is a name that specifies a set of *event types* to be shown. In Sherpa, click on the Event tab in the leftmost display pane; all event types for the currently loaded simworld are displayed with checkboxes. The Show Level menu allows selection among predefined show levels. Selecting a show level causes event type checkboxes associated with that show level to become checked. In Lisp, show levels are set with the *show* function when used in the following form:

(show :level <level-name>)

where level-name is a symbol *without* quotes. Predefined show levels are described in Appendix A.

2. Using Sherpa, specify particular event-types of interest. Select the event tab as above, then click on checkboxes to toggle whether or not to have a particular event type shown. Note that selecting or unselecting event types modifies the choices associated with the previous show-level, though that show-level is still displayed on the interface. In Lisp, event types are selected with the show function when used in the following form:

(show <event-type>)

where <event-type> is a symbol *without* quotes. Event types are listed in Appendix A.

3. In Lisp (but not Sherpa), it is possible to filter events on parameters other than, and in addition to, event types. Like the previous features, this is done using the show function. The show function is described in Appendix A.

3.5.5 Directing output to a file

Traces may be saved in a file by typing the following form in the listener:

(save-trace <filename>)

where filename is a string and may either be a full pathname, or just a filename. In the latter case, the trace is saved in the current simworld's directory.

3.5.6 Generating and examining PERT charts

In Sherpa, a PERT chart for a simulation run may be generated by clicking the PERT chart button located above the trace view pane. A new tab for the PERT chart is created and displayed. PERT charts cannot be generated by direct commands from Lisp. The PERT chart view can be manipulated in several ways.

- A slider bar provides zoom control
- The expand/contract buttons control distance between PERT boxes
- The timeline button toggles between a PERT view and a timeline view

3.5.7 Exporting a PERT chart to Powerpoint

Sherpa cannot create Microsoft Powerpoint representations of PERT charts directly. Instead, it outputs Visual Basic macros that can be read in from Powerpoint. PERT charts you create using the procedure below will not likely fit onto one slide, but will tend to trail off the right hand edge. You'll need to edit charts in Sherpa and/or Powerpoint to get good results.

1. Create a PERT chart in Sherpa

2. In Sherpa, press the button with the PowerPoint icon. Then select a folder and filename at the prompt. A Visual Basic macro representing the PERT chart will be written out at this location.

3. From Powerpoint select from the menu: *Tools* > *Macro* > *Visual Basic Editor*. This will open the visual basic editor.

4. From Powerpoint, load the macro created in step 2

> On a Mac: From the Visual Basic interface, select *Insert* > *Module*. Select *Insert* > *File*… Set the *Show* field in the dialog selection box to *All Files*. Select the file you created in step 2.
>
> On a PC: From the Visual Basic interface, select *File* > *Import File*. Select the file you created in step 2.

5. Return to Powerpoint and click on the slide to contain the PERT chart. Select from the menu: *Tools* > *Macro* > *Macros* and run the macro "CreatePERTChart". For a large PERT chart, this may take a few moments to complete.

Note: To remove files created in step 2 (which will otherwise accumulate), go to the Visual Basic editor and select *Module*X in the Project window. From the menu, then select: *File* > *Remove Module*X.

3.6 System patches

Patches provide extensions or modifications or fixes to the existing Apex software without requiring reinstallation. Users can acquire patches from:

ftp://eos.arc.nasa.gov/outgoing/apex/apex/patches/

Download all of the .lisp files in this directory and put them in your apex/patches directory. Delete any existing versions of the same files if needed, including any compiled versions (e.g. those ending in .fasl). The patches will automatically be in effect the next time you start Apex. If you wish to install the patches without restarting Apex, type *(load-patches)* at the Lisp prompt. A brief description of each patch is found in the file.

3.7 Getting Help

If you experience problems with Apex, please consult the Troubleshooting sections in this manual and of your Apex installation instructions. If necessary, contact the Apex development team by sending email to:

apexhelp@eos.arc.nasa.gov

Email is the strongly preferred means of technical support, and probably receives faster response than any other means of contact.

If you are reporting what appears to be a bug, first see if you can reproduce it. Please include the following information in your email:

- Detailed description of the problem, including any error messages that appeared (in their entirety, cut and pasted if possible), the last thing you did before the problem occurred, and whether you could reproduce the problem.

- Your operating platform: type of computer and operating system, version of Apex (in "Help" menu of Sherpa), and version of Common Lisp (if applicable).

4.0 Procedure Description Language (PDL)

> *By relieving the brain of all unnecessary work, a good notation sets it free to concentrate on more advanced problems, and, in effect, increases the mental power of the race.*
>
> - Alfred North Whitehead

Procedure Description Language (PDL) is a formal language used to specify the behavior of Apex agents. PDL can be seen as a means of representing particular kinds of content – e.g. normative human behavior as defined by standard operating procedures; a task analysis describing observed or expected behavior; a cognitive model reflecting human procedural and declarative memory. However, making effective use of PDL requires also understanding it as a programming language for invoking the capabilities of the Apex action selection architecture. This section describes the syntax of PDL following a brief overview of the workings of the action selection architecture – see (Freed 1998) for more detail.

The central language construct in PDL is a procedure, which contains at least an index clause and one or more step clauses. The index uniquely identifies the procedure and typically describes what kind of task the procedure is used to accomplish. Each step clause describes a subtask or auxiliary activity prescribed by the procedure.

```
(procedure
  (index (turn-on-headlights)
  (step s1 (clear-hand left-hand))
  (step s2 (determine-location headlight-ctl => ?loc)
  (step s3 (grasp knob left-hand ?loc) (waitfor ?s1 ?s2))
  (step s4 (pull knob left-hand 0.4) (waitfor ?s3))
  (step s5 (ungrasp left-hand) (waitfor ?s4))
  (step s6 (terminate) (waitfor ?s5)))
```

The procedure above, representing a method for turning on the headlights in some cars, illustrates several important aspects of PDL. One important point is that a procedure's steps are not necessarily carried out in the order listed or even in a sequence. Instead, steps are assumed to be concurrently executable unless otherwise specified. If step ordering is desired, a waitfor clause is used to specify that the completion (termination) of one step is a precondition for the start (enablement) of another. In the example above, the steps labeled s1 and s2 do not contain waitfor clauses and thus have no preconditions; these steps can begin execution as soon as the procedure is invoked and can run concurrently. Step s3, in contrast, includes the clause *(waitfor ?s1 ?s2)* . This means that step s3 becomes enabled only when steps s1 and s2 have terminated.

Procedures are invoked to carry out an agent's active tasks. Tasks, which can be thought of as agent goals[6], are stored on a structure called the agenda internal to the action selection architecture. When a task on the agenda becomes enabled (eligible for immediate execution), what happens next depends on whether or not the task corresponds to a primitive action. If so, the specified action is carried out and then the task is terminated. There are a limited number of primitive action types (see section 4.3), each with a distinct effect.

If the task is not a primitive, the action selection architecture retrieves a procedure whose index clause matches the task. For example, a task of the form *(turn-on-headlights)* matches the index clause of the procedure above and would thus be retrieved once the task became enabled. Step clauses in the selected procedure are then used as templates to generate new tasks, which are then added to the agenda. It is conventional to refer to these tasks as subtasks of the original and, more generally, to use genealogical terms such as child and parent to describe task relationships. In this example, there are six steps so six new tasks will be created. The process of decomposing a task into subtasks on the basis of a stored procedure is called task refinement. Since some of the tasks generated through this process may themselves be non-primitive, refinement can be carried out recursively. This results in the creation of a task hierarchy.

An Apex agent initially has on its agenda a single task of the form *(do-domain)*. All agent behavior results from tasks descending hierarchically from the do-domain task. Thus, the specification of agent behavior for a given application (model) must include a procedure with the index clause *(index (do-domain))* to bootstrap (initialize) behavior. Steps of the do-domain procedure should specify not only the main "foreground" activities of the agent, but also any appropriate background activities (e.g. low priority maintenance of situation awareness) and even reflexes (e.g. pupil response to light).

4.1 The action selection architecture

The Action selection architecture[7] (AA) is the algorithm Apex uses to generate behavior. Input to the algorithm consists of events that the agent might respond to and a set of predefined PDL procedures. The architecture outputs commands to resources. When used to generate behavior for a simulated human agent, resources are representations of cognitive, perceptual and motor faculties such as hands and eyes. Since the action selection architecture could be used to model other entities with complex behavior such as robots and autopiloted aircraft, resources could correspond to, e.g., robotic arms or flight control surfaces. The action selection architecture incorporates a range of functional capabilities accessible through PDL. These functions fall into four categories:

---

[6] The term task generalizes the concept of a classical goal – i.e. a well-defined state, expressible as a proposition, that the agent can be seen as desiring and intending to bring about (e.g. "be at home"). Tasks can also, e.g., encompass multiple goals ("be in car seat with engine started and seatbelt fastened"), specify goals with indefinite state ("finish chores"), specify goals of action rather than state ("scan security perimeter "), and couple goals to arbitrary constraints ("be at home by 6pm").

[7] Designated the Action Selection Architecture in other documents. To some, this term implies that the architecture performs AI planning tasks, but not scheduling or control. The term Action selection architecture was chosen to be happily ambiguous about the underlying technology.

- hierarchical action selection
- reactive control
- resource scheduling
- general programming language functions

Hierarchical action selection refers to the process of recursively decomposing a high-level task into subtasks, down to the level of primitive actions. The basic process of selecting action by hierarchical task decomposition is simple. Tasks become enabled when their associated preconditions have been satisfied. If the task is not a primitive, a procedure whose index clause matches the task is retrieved and one new task (subtask) is created for each step of the selected procedure. If the enabled task is a primitive, the specified action is executed and the task is terminated.

PDL provides flexibility in controlling how and when task decomposition takes place. The issues of *how* to decompose a task arises because there are sometimes alternative ways to achieve a goal, but which is best will vary with circumstance. Criteria for selecting between different procedures are represented in the index clause (see section 4.2.2) and the select clause (4.2.5). The issue of *when* to decompose a task is equally crucial since an agent will often lack information needed to select the appropriate procedure until a task is in progress. The ability to specify what needs to be known in order to select a procedure (informational preconditions) is provided by the waitfor clause (4.2.4).

Reactive control refers to a set of abilities for interacting in a dynamic task environment. As noted above, the ability to cope with uncertainty in the environment sometimes depends on being able to delay commitment to action; when crucial information becomes available, the agent can select a response. Another aspect of reactivity is the ability to handle a range of contingencies such as failure, interruption, unexpected side-effects, unexpectedly early success and so on. Integrating contingency-handling behavior with nominal behavior is quite challenging and benefits from building certain principles and heuristics into the architecture. For example, Apex incorporates a heuristic preference for continuing an ongoing task over allowing a new task to interrupt. The preference can be increased or negated using the interrupt-cost construct (4.2.10).

Reactive mechanisms combined with looping (4.2.6) and branching (4.2.2; 4.2.4; 4.2.5) allow closed-loop control – i.e. the ability to manage a continuous process based on feedback. The combination of a discrete control mechanisms such as hierarchical action selection with a continuous control mechanisms allows PDL to model a wide range of behaviors.

Resource scheduling refers to the ability to select execution times that meet specified constraints for a set of planned actions. Typically, an overriding goal is to make good (possibly optimal) use of limited resources. Actions can be scheduled to run concurrently unless they conflict over the need for a non-sharable resource (e.g. a hand) or are otherwise constrained. For example, an eye-movement and an unguided hand movement such as pulling a grasped lever could proceed in parallel. PDL includes numerous clauses and primitive action types for dynamically asserting, retracting and parameterizing scheduling constraints (4.2.4; 4.2.8; 4.2.9; 4.2.10; 4.3.5; 4.3.6; 4.3.7).

Scheduling is tightly integrated with reactive control and hierarchical planning. In a less tightly integrated approach, these functions might be assigned to modular

elements of the architecture and carried out in distinct phases of its action decision process. In Apex, these activities are carried out opportunistically. For example, when the information to correctly decompose a task into subtasks becomes available, the architecture invokes hierarchical planning functions. Similarly, when there are a set of well-specified tasks and scheduling constraints on the agenda, Apex invokes scheduling functions.

This has two important implications for the role of scheduling in Apex. First, scheduling applies uniformly to all levels in a task hierarchy. In contrast, many approaches assume that scheduling occurs at a fixed level – usually at the "top" where a schedule constitutes input to a planner. Second, the tasks and constraints that form input to the scheduler must be generated dynamically by hierarchical planning and reactive control mechanisms, or inferred from local (procedure-specific) constraints, evolving resource requirements, and changes in the execution state of current tasks. Basic scheduling capabilities can be employed without a detailed understanding of the architecture. For more advanced uses of these capabilities, it is hoped that the PDL construct descriptions will prove helpful. Further information can be found in Freed (1998a, 1998b).

PDL includes language constructs for typical programming language functions such as looping and branching. However, the user will sometimes wish to access data or functions not directly supported in PDL but available in the underlying Lisp language. PDL supports callouts to Lisp that apply to different aspects of task execution including: precondition handling (4.2.4; appendix D), action selection (4.2.5), specification of execution parameters (4.2.6; 4.2.9; 4.2.10; 4.2.11) and specification of the actions themselves (see "special procedures" in 4.2.1).

4.2 PDL Syntax

PDL syntax will be described using the following conventions:

- ( ) all PDL constructs are enclosed by parentheses
- [ ] square-brackets enclose optional parameters
- < > angle-brackets enclose types rather than a literal values
- | vertical bars separate alternative values
- { } curly brackets enclose alternatives unless otherwise enclosed
- X^+ means that 1 or more instances of X are required
- X^* means that 0 or more instances of X are required

In addition, the following terms are used. A procedure-level clause is a language construct embedded directly in a PDL procedure. Examples include index clauses and step clauses. Step-level clauses such as waitfor are embedded directly in a step clause. The procedure construct is itself a first-class construct, meaning that it is not embedded in any other language element. A pattern parameter is a parenthesized expression that may contain variables (denoted as a symbol starting with a question-mark such as ?x). Patterns, which are matched against each other by the pattern matcher (see appendix D), appear in several PDL clauses. A Lisp symbol is a sequence of characters that that may include alphanumerics, dashes, and some other characters. A Lisp symbolic expression, or s-expression, is either a Lisp symbol or a list of symbols and Lisp expressions enclosed

by parentheses. An Apex variable is a symbol whose first character is a question-mark – e.g. ?x. Symbols and s-expressions in PDL clauses may contain Apex variables.

4.2.1 Procedure

first-class construct

(procedure [:concurrent] <index-clause> <procedure-lvl-clause>$^{+}$)
(procedure [:sequential|:ranked] <index-clause> <step-clause>$^{+}$)
(procedure :special <index-clause> <procedure-level-clause>$^{+}$ <s-expression>)

There are four types of procedures: concurrent, sequential, ranked and special. All types must contain an index clause. By default, procedures are of type concurrent. This means that all tasks generated from the procedure's steps are assumed to be concurrently executable, except where ordering is specified by waitfor clauses. A concurrent procedure will usually include an explicit termination step such as *s4* in the example procedure below left. In this case, the parent task *{task-15 (open door)}* will terminate when the last of its subtasks *{task-18 (push)}* terminates.

```
(procedure
  (index (open door))
  (step s1 (grasp door-handle))
  (step s2 (turn door-handle) (waitfor ?s1))
  (step s3 (push) (waitfor ?s2))
  (step s4 (terminate (waitfor ?s3))))
```

As in this example, it is quite common to define procedures consisting of a totally ordered set of steps. Such procedures can be conveniently represented using the sequential procedure syntax. The following example is equivalent to the concurrent procedure above.

```
(procedure :sequential
  (index (open door))
  (grasp door-handle)
  (turn door-handle)
  (push))
```

A sequential procedure includes only an index clause and a list of steps to be carried out in the listed order. No terminate clause is specified. Only the activity-description argument of each step is specified; the symbol `step`, the step-tag argument and step-level clauses are not required or allowed. Sequential procedures are not really a separate type, but an alternative syntax. PDL mechanisms automatically translate them into equivalent concurrent procedures by adding a terminate step and waitfor clauses as needed to specify step order.

Ranked procedures abbreviate a concurrent procedure form in which rank clauses (4.2.13) are added to each step. Rank values in these procedures are in ascending order of appearance . Thus, the following two procedures are equivalent:

```
(procedure                                    (procedure :ranked
  (index (open door))                           (index (open door))
  (step s1 (grasp door-handle) (rank 1))        (grasp door-handle)
  (step s2 (turn door-handle) (rank 2))         (turn door-handle)
  (step s3 (push) (rank 3))                     (push))
  (step s4 (terminated) (waitfor ?s1 ?s2 ?s3)))
```

Special procedures are a way to call Lisp code directly during task execution. This is useful for controlling and accessing data from processes external to the action selection architecture and for carrying out functions that would be awkward or impossible to represent purely in PDL. In the first example below, the procedure uses the simulation engine function end-trial to stop the simulation from continuing (perhaps indefinitely) past the point of interest.

```
(procedure :special
  (index (stop simulation trial))
  (end-trial))
```

In the next example, a special procedure is used to compute the distance between two points in a plane. Values returned by the Lisp body of a special procedure are bound to variables in the return value form (if any) of the calling step (see 4.2.3). Thus, executing a step such as *(step s5 (compute-distance ?p1 ?p2 => ?d) (waitfor ?s4))* would cause the procedure to be called and its return value bound to the variable *?d*.

```
(procedure :special
  (index (compute-distance ?point1 ?point2))  ; points are lists of the form (x y)
  (sqrt (exp (- (first ?point1) (first ?point2)) 2)
        (exp (- (second ?point1) (second ?point2)))))
```

Special procedures may include procedure-level clauses other than index, but may not include any step clauses. When a task for which a special procedure has been selected becomes enabled, that task is executed and then terminated just as if it were a primitive action.

4.2.2 Index

procedure-level clause

(index <pattern>)

Each procedure must include a single index clause. The index pattern uniquely identifies a procedure and, when matched to a task descriptor, indicates that the procedure is

appropriate for carrying out the task. The pattern parameter is a parenthesized expression that can include constants and variables in any combination. The following are all valid index clauses:

```
(index (press button ?button))
(index (press button ?power-button))
(index (press button ?button with hand))
(index (press button ?button with foot))
```

Since index patterns are meant to uniquely identify a procedure, it is an error to have procedures with non-distinct indices. Distinctiveness arises from the length and constant elements in the index pattern. For example, the first and second index clauses above are not distinct since the only difference is the name of a variable. In contrast, the 3rd and 4th index clauses are distinct since they differ by a constant element.

Apex uses the pattern matcher from Norvig (1992) which provides a great deal of flexibility in specifying a pattern. For example, the following index clause includes a constraint that the pattern should not be considered a match if the value of the variable is self-destruct-button.

```
(index (press button ?button (?if (not (eql ?button ?self-destruct-button)))))
```

In the next example, the variable ?button-list will match to an arbitrary number of pattern elements. This provides the flexibility to create a procedure that presses a list of buttons without advance specification of how many buttons will be pressed.

```
(index (press buttons (?* button-list)))
```

See Norvig (1992) and appendix D for more information on the pattern matcher.

4.2.3 Step

procedure-level clause

(step <step-tag> <step-description [=> {var|pattern}]> [step-level-clause])*

Step clauses in a procedure specify the set of tasks to be created when the procedure is invoked and may contain additional information on how the tasks should be executed (e.g. ordering constraints). Each step must contain a step-tag and step-description; optionally, an output variable and/or any number of step-level clauses may be added.

A step-tag can be any symbol (as defined by Lisp), although no two steps in a procedure can use the same tag. Step-tags provide a way for steps in a procedure to refer to one another. In particular, whenever a new task is created from a procedure step, the action selection architecture creates a variable based on the step tag and binds that variable to the new task. E.g. when *(step s4 (go west))* is used to create *{task-92 (go west)},* the variable *?s4* is created and bound to the data structure for task-92. The task refinement process also generates the variable *?self* which is bound to the task being

refined – i.e. the parent to task-92 in this example. This allows subtasks to refer to their parent task.

The step-description, the part of the step clause that describes behavior, must be a parenthesized expression corresponding either to the index of one or more procedures in the agent's procedure library or to a PDL primitive action type (see section 4.3). It may contain variables. When a task is enabled, the value of the task description is set to equal the step description with any variables replaced by values. The task description is used to invoke a primitive action is appropriate, or if not, matched against procedure index clauses to select the correct procedure.

The step-description may include the special symbol => followed by a variable or other pattern. This specifies one or more output variables which become to a return-value produced when the task derived from a step terminates. Thus,

(step s1 (find volume control => ?location))

would create a task such as *{task-22 (find volume control)}*. When this task terminates, it should supply a return value which will be bound to the variable *?location*. See the description of the terminate primitive (section 4.3.2) for a description of how return-values are generated.

It is an error for a task-description to contain a variable whose value is undefined at the time the task is enabled. This is avoided by making task-specifiability a precondition using waitfor clauses. Some waitfor preconditions bind values directly. For example, *(waitfor (on ?object table))* not only waits for something to be on the table but also binds the variable *?obj*ect as a side-effect. Other preconditions wait for the completion of tasks that insure a variable gets bound. For example, if step s2 waits for step s1 above to complete, this insures that the variable ?*location* will be bound when s2 a procedure for s2 is selected.

4.2.4 Waitfor

step-level clause

(waitfor {<pattern>|<step-tag-variable>}$^{+}$ [:and <test>$^{+}$])

A waitfor clause defines a set of task preconditions which must be satisfied for the task to become enabled – i.e. eligible for execution. Each pattern argument defines a single precondition that is unsatisfied when the task is created. The precondition is considered satisfied when a **cogevent** matching the pattern is detected. Cogevents are representation of events that have become available to the action selection architecture. Some cogevents are generated by the action selection architecture and reflect occurrences within it (e.g. an event signaling that some task has terminated). Others are generated externally, typically by agent perceptual resources such as vision (e.g. to signal that an object has been detected).

It is important to note that waitfor preconditions are satisfied by events, not by states represented in memory. For example, if a task comes into existence with a precondition of the form *(on book table)* and a proposition of the same form exists in

memory[8], this will not satisfy the precondition; the task will remain in a pending (non-enabled) state until matched to a corresponding cogevent. The action selection architecture prescribes no particular method for detecting when preconditions are satisfied in the current state. One possibility is to include a step in the procedure to explicitly check whether a precondition is satisfied, either perceptually or by memory retrieval. Note: only allowing events to satisfy preconditions facilitated specification of reactive behavior since it will sometimes be desirable to act only in response to change.

Waitfor clauses are useful for specifying execution order for steps of a procedure. This is accomplished by making the termination of one step a precondition for the enablement of another. The action selection architecture generates events of the form *(terminated <task>)* when a task is terminated, so a clause such as *(waitfor (terminated ?s3))* will impose order with respect to the task bound to the task-tag-variable ?s3 (see 4.2.3 for information on task-tag-variables). Termination preconditions can be expressed using an abbreviated form: *(waitfor <task-tag-var>)) == (waitfor (terminated <task-tag-var>))*. Thus, the expression *(waitfor ?s3)* is equivalent *(waitfor (terminated ?s3))*.

Preconditions in a waitfor clause are conjunctive; all must be satisfied for the task to become enabled. Tests (s-expressions) optionally following the keyword *:and* essentially add additional conjunctive preconditions. These (special) preconditions are evaluated after all of the normal preconditions (specified before the *:and*) are satisfied. If any of these expressions evaluate to nil, the special precondition is considered unsatisfied and the task does not become enabled. Moreover, it can never become enabled since the tests are not performed again. This restricts the use of special conditions to representing conditional branches in a procedure. In the following example, the agent's behavior depends on the relative value of the variables *?my-score* and *?his-score*.

```
(step s1 (cackle with glee)
   (waitfor (final-score ?my-score ?his-score :and (>= ?my-score ?his-score))))
(step s2 (sulk despondently)
   (waitfor (final-score ?my-score ?his-score :and (< ?my-score ?his-score))))
```

It is possible to specify disjunctive preconditions using multiple waitfor clauses. For example, step s2 prescribes terminating a hole-digging task if either the hole has been dug to the specified depth or if the shovel needed to dig the breaks.

```
(step s1 (dig hole ?depth))
(step s2 (terminate)
    (waitfor ?s1)
    (waitfor (broken shovel)))
```

Correctly specifying waitfor preconditions is perhaps the trickiest part of PDL. On important issue arises from the fact that, in Apex, preconditions are satisfied independently, not jointly as might sometimes seem more intuitive. For example, one might want to express a behavior that becomes enabled in response to a red light,

[8] The Apex architecture does not include a built-in memory for world-state. Typically, this function is handled by a resource component defined to take encode and retrieve commands from the agent mechanisms.

representing this with *(waitfor (color ?object red) (luminance ?object high))*. However, vision might detect *stopsign-1* that is red but not a light and generate a cogevent of the form *(color stopsign-1 red)*. This will satisfy the first listed precondition, binding the variable *?object* to *stopsign-1*. The second precondition will then remain unsatisfied unless *stopsign-1* becomes highly luminant. Planned improvements to PDL will provide the flexibility to express joint preconditions.

4.2.5 Select

step-level clause

(select <variable> <s-expression>)

The select clause is used to choose between alternative procedures for carrying out a task. Its influence on selection is indirect. The direct effect of a select clause is to bind the specified variable to the evaluation of the Lisp-expression argument. This occurs as the task becomes enabled, just prior to selecting a procedure for the associated task, so instances of the variable in the task description will be replaced by the new value and may affect procedure selection.

```
(step s1 (press ?button with ?extremity)
        (select ?extremity (if (> (height ?button) .5) 'hand 'foot)))
```

In the example above, the value of the variable *?extremity* is set to *hand* if the button is more than .5 meters off the ground, otherwise it is set to *foot*. Assuming procedures with index clauses *(index (press ?button with hand))* and *(index (press ?button with foot))*, the effect of the selection clause is to decide between the procedures.

known bug: a step may only contain one select clause

4.2.6 Period

step-level clause

(period :recurrent [<test>] [:enabled [<test>]] [:reftime {enabled|terminated}]
[:recovery <interval>])

The period clause is used to create and control repetition. The simplest form of the clause, *(period :recurrent)* declares that the task should be restarted immediately after it terminates and repeat continuously. In this case, repetition will only cease when its parent task terminates or the task is explicitly terminated (by a terminate primitive action). The optional test condition is a Lisp expression that is evaluated; if nil, the task does not repeat. This makes the task behave as if in a repeat-until loop.

By default, any waitfor preconditions associated with a recurrent task are reset to their initial unsatisfied state when the task restarts. If present, the optional *:enabled* argument causes the task to restart in an enabled state – i.e. with preconditions satisfied.

An optional test for enablement is evaluated at restart-time; if it evaluates to nil, the task is restarted with all preconditions unsatisfied as in the default case.

The optional :*reftime* argument is used to specify whether to start a new instance of the task when the old instance terminates or when the old instance becomes enabled. Restarting at termination time is the default, producing repetition in the normal sense. If the value of reftime equals *enabled*, the task does not repeat; instead a whole new instance of the task is created, coexisting with the current one. This option is provided as a way to specify response policies – i.e. that a response task should be generated to a given class of events even if one or more such response tasks are already ongoing.

```
(step s5 (shift-gaze ?visob)
    (waitfor (new (visual-object ?visob)))
    (period :recurrent :reftime enabled))
```

For example, the step above represents a policy of shifting gaze to any newly appearing object, even if it appears while in the process of shifting gaze to a previously appearing object. If the task only recurred at terminate-time, objects appearing during a previous gaze-shift response would be ignored. To prevent infinite generation of new task instances, steps specified with enable-time recurrences cannot be restarted in enabled state. Thus, the enabled parameter must be nil (the default) and the step must include waitfor preconditions.

The *:recovery* argument temporarily reduces a repeating task's priority (4.2.9) in proportion to the amount of time since the task was last executed. This reflects a reduction in the importance or urgency of reexecuting the task. For example, after checking a car's fuel gauge, there is no reason to do so again soon afterwards since little is likely to have changed. In the following example, the priority of task for repeatedly monitoring the fuel gauge is reduced to 0 immediately after performing the task, and gradually rises to its full normal value over a period of 30 minutes.

```
(step s5 (monitor fuel-gauge) (period :recurrent :recovery (30 minutes)))
```

4.2.7 Forall

step-level-clause

(forall <var> in {<var>|<list>})

The forall clause is used to repeat an action for each item in a list. For example, the following step prescribes eating everything in the picnic basket.

```
(step s3  (eat ?food)
    (forall ?food in ?basket-contents)
    (waitfor ?s2 (contents picnic-basket ?basket-contents))
```

The effect of a forall clause is to cause a task to decompose into a set of subtasks, one for each item in the list parameter. Thus, if the step above generates *{task-12 (eat ?food)}*

and the cogevent *(contents picnic-basket (sandwich cheese cookies))* occurs, the variable *?basket-contents* will become bound to the list *(sandwich cheese cookies)*. Later, when the task bound to *?s2* is terminated, *task-12* becomes enabled. Normally, the action selection architecture would then select a procedure for *task-12*. The forall clause takes effect just prior to procedure selection, creating a set of new tasks for each item in the forall list. Each of these is a subtask of the original. In this example, the forall clause would result in subtasks of *task-12* such as *{task-13 (eat sandwich)}*, *{task-14 (eat cheese)}* and *{task-15 (eat cookies)}*. Procedures would then be selected for each of the new tasks.

```
(step s1 (examine indicator ?indicator)
    (forall ?instrument in (fuel-pressure air-pressure temperature))
    (period :recurrent))
```

Note that forall can be combined with period. In the example above, the step prescribes repeatedly examining a set of instruments.

4.2.8 Profile

procedure-level clause

(profile <resource>$^{+}$)

The profile clause lists discrete resources required for using a procedure.[9] Whenever the procedure is selected for a task, the resource requirements become additional preconditions (beyond those prescribed by waitfor clauses) for beginning execution of the task. For example, the following procedure declares that if selected as a method for carrying out a task, that task cannot begin execution until the action selection architecture allocates to it a resource named *right-hand*.

```
(procedure
  (index (shift manual-transmission to ?gear))
  (profile right-hand)
  (step s1 (grasp stick with right-hand))
  (step s2 (determine-target-gear-position ?gear => ?position))
  (step s3 (move right-hand to ?position) (waitfor ?s1 ?s2))
  (step s4 (terminate) (waitfor ?s3)))
```

The profile may specify resources as variables as long as these are specified in the index clause. For example, the procedure above could be specified as follows:

```
(procedure
  (index (shift manual-transmission to ?gear using ?hand))
```

[9] The profile clause is only used for "blocking" resources such as hands and eyes that can only be allocated to one task at a time, but may be reallocated freely. There are currently no mechanisms to support reasoning about "depletable" resources such as fuel or money.

(profile ?hand)
…)

Resource preconditions are not determined until a procedure is selected, and therefore not after all waitfor preconditions have been satisfied. Thus, the architecture only makes allocation decisions for tasks that are enabled or already ongoing. The architecture allocates resources to tasks based on the following rules:

1. A task is competing for the resources listed in its profile if it is either enabled (all waitfor preconditions satisfied) or already ongoing
2. If only one task competes for a resource, it is allocated to that task
3. If multiple tasks compete for a resource, allocation is awarded to the task with highest priority (see 4.2.9)
4. If one of the tasks competing for a resource is already ongoing (and thus has already been allocated the resource), its priority is increased by its interrupt-cost (4.2.10). By default, interrupt cost is slightly positive, producing a weak tendency to persist in rather than interrupt a task.
5. Tasks at any level in a task hierarchy may require and be allocated resource. A task does not compete with its own ancestor.
6. If a profile lists multiple resources, it is allocated all of them or none. If there is a resource for which it is not the highest priority competitor, then it does not compete for the other resources and any resources already allocated become deallocated. This rule takes precedence over rules 2 and 3.

Resources listed in a profile clause do not necessarily correspond to components of the agent resource architecture, the collection of modules that either provide information to the action selection architecture or can be commanded by it using the primitive action start-activity (4.3.1). Resources named in a profile clause that do not correspond to an element of the resource architecture are **virtual resources.**

4.2.9 Priority

step-level clause

(priority {<integer>|<variable>|<s-expression>})

A priority clause specifies how to assign a priority value to a task in order to determine the outcome of competition for resources. The assigned value is a unitless integer. It can be specified as a fixed value, as a variable that evaluates to an integer or as an arbitrary Lisp s-expression.

A task's priority is first computed when it becomes enabled, is matched to a procedure that requires a resource (i.e. includes a profile clause) and is found to conflict with at least one other task requiring the same resource. If the task is not allocated a needed resource, it remains in a pending state until one of several conditions arise, causing it to again compete for the resource. These conditions are: (1) the resource is deallocated from a task that currently owns it, possibly because that task terminated; (2)

new competition for that resource is initiated for any task; (3) the primitive action reprioritize (4.3.5) is executed on the task. Whenever a task begins a new resource competition, its priority is recomputed.

A step may have multiple priority clauses, in which case, the priority value from each clause is computed separately. The associated task is assigned whichever value is the highest. This value is the local priority value. Tasks may also inherit priority from ancestor tasks. A task could have one or more inherited priorities but no local priority. Alternately, it may have no inherited priorities but a local priority. In all cases, task priority equals the maximum of all local and inherited values.

Note: In some cases, a task will become interrupted but one or more of its descendant tasks will become or remain ongoing. These descendants no not inherit priority from the suspended ancestor.

4.2.10 Interrupt-cost

step-level clause

(interrupt-cost {<integer>|<variable>|<s-expression>})

Interrupt-cost specifies a degree of interrupt-inhibition for an ongoing task. Interrupt cost is computed whenever the task is ongoing and competing for resources – i.e. resources it has already been allocated and is "defending." The value is added to the task's local priority.

4.2.11 Assume

procedure-level clause

(assume <var> <proposition> <duration>)

An assume clause declares that a specified proposition should be treated as an assumption. By default, the variable specified in the assume clause is set to T, indicating that the assumption has not been contradicted. If a cogevent that contradictions does occur, the value of the variable is set to nil. After an amount of time passes equal to the duration parameter, the value reverts to T.

The assume clause is meant to be used for procedure selection, allowing the architecture to select alternative means for carrying out a task in non-standard conditions. For example, the following procedure selects route B (rather than route A as usual) for getting home from work if there is accident on highway-5.

```
(procedure
  (index (get home from work))
  (assume ?clear-path (accident-on-path route-a false) (1 day))
  (step s1 (enter and start car))
  (step s2 (drive route ?selected-route)
    (select ?selected-route (if ?clear-path 'route-a 'route-b)))
```

```
    (waitfor ?s1))
  (step s3 (terminate) (waitfor ?s2)))
```

One very unusual aspect of the assume clause is that it applies not to tasks, but to procedures. In other words, the presence of the procedure in the procedure set of an agent causes the agent to track the specified assumption. If an event contradicting the assumption occurs, this is reflected in the value of the assume variable even if the procedure has not been selected for any current tasks. If such a task comes into existence during the interval between a detected violation of the assumption and the time when the assumption variable reverts to T, the assume variable will have the value nil for that task.

A cogevent is considered to violate the specified assumption if the assumption proposition ends in a Boolean value (T, nil, true, false) and the cogevent has the same form with the last value in the form holding the opposite value. For example, a cogvent of the form (accident-on-path route-a true) would violate the assumption in the example above. Assumption violation also occurs if a cogevent occurs indicating a changed value in a fluent proposition. For example, the cogevent *(color danger-indicator red)* violates an assumption proposition of the form *(color danger-indicator green)* as long as color propositions have been declared fluents (4.2.12).

To track the truth value of declared assumptions, the architecture automatically generates a procedure with *(index (monitor-assumptions))* and steps for monitoring each assumption specified in an assumption clause. The example above would cause a step such as the following (simplified)

```
(step g813 (set-temporary-value ?selected-route nil (1 day))
        (waitfor (accident-on-path route-a true))
        (period :recurrent))
```

to be added to the monitor assumptions procedure. This procedure is automatically selected and executed when the agent is initialized, so assumption monitoring is always active. Since the assumption variable is an Apex global variable, the value is not tied to the creation or termination any task and is accessible to all tasks.

4.2.12 Declare-fluent

First-class construct

(declare-fluent <pattern> <var-list>)

Fluents are propositions that can contradict other, similar. propositions; if presented in temporal sequence, they can make other propositions obsolete. For example, propositions 1 and 2 below are contradictory because, quantum mechanics aside, a device cannot be both on and off at the same time. If proposition 1 is presented, followed at some later time by 2, this can interpreted as a change of state that makes 1 obsolete. Propositions 3 and 4, in contrast are not in contradiction because an object can be inside multiple containers.

(1) (power television-1 on)
(2) (power television-1 off)
(3) (in television-1 living-room-1)
(4) (in television-1 house-1)

The declare-fluent construct specifies a that a given propositional form is a fluent. The pattern parameter is a list containing constants and variables. The variable-list parameter identifies pattern elements that determine whether the two proposition are potentially in conflict. Actual conflict requires some difference in value in any remaining variable element. For example, given

(declare-fluent (power ?device ?state) (?device))

propositions 1 and 2 above both match the fluent pattern. Because they have the same value for ?*device*, they are potentially in conflict. Because, they have different values for the remaining variable specified in the fluent pattern (i.e. ?*state*), they are actually in conflict. The propositions below, in contrast, do not conflict with either 1 or 2.

(5) (power television-2 off)
(6) (weight television-1 100)

Fluent definition are used in conjunction with the assume clause (4.2.11) and can be used to define the information handling behavior of agent resources such as vision and memory.

4.2.13 Rank

step-level clause

(rank {<integer>|<variable>|<s-expression>})

Like a priority clause, a rank clause specifies how to determine the outcome of competition for resources. The assigned value is a unitless integer. It can be specified as a fixed value, as a variable that evaluates to an integer or as an arbitrary Lisp s-expression. Rank values are computed whenever priority values are computed (4.2.9).

Though also used to resolve resource conflicts, rank is very different form priority. Whereas a task's priority is an intrinsic (globally scoped) property, its rank depends on what task it is being compared to. For example, consider the procedure below:

```
(procedure
  (index (record phone number of ?person))
  (step s1 (determine phone-number of ?person) (rank 1))
  (step s2 (write down phone-number of ?person) (rank 2))
  (step s3 (terminate) (waitfor ?s1 ?s2)))
```

This procedure specifies that activities related to determining a specified person's phone number can be carried out in parallel with activities for writing the number down – i.e. the latter task and all of its descendant subtasks (e.g. {task-25 (grasp pencil)}) do not have to wait for the former task to complete. However, resource conflicts will automatically be resolved in favor of the better ranked task – i.e. the one with the lower priority value. Thus, if {task-25 (grasp pencil)} and {task-22 (grasp phone book)} both need the right hand, the latter task will be favored since it descends from a task with superior rank.

To determine rank for two conflicting tasks A and B, the architecture locates a pair of tasks A' and B' for A' is an ancestor of A, B' is an ancestor of B, and A' and B' are siblings – i.e. derived from the same procedure. If no rank is specified for A' and B', A and B have no rank relative to one another. Resource conflict is then resolved based on priority (4.2.9). Otherwise, rank values for A' and B' are inherited and used to resolve the conflict.

4.3 Primitives

Primitives are actions whose effects are defined by the Apex architecture rather than by a PDL procedure. They cannot be further decomposed into more fundamental tasks. The term **operator** is used for behaviors that are low-level from the point of view of a particular domain or task model. For example, in some models of human-computer interaction, behaviors such as pushing a button and moving a mouse to a target location might be considered operators. Operators are generally represented as PDL procedures that employ primitives, particularly **start-activity**. The full set of Apex primitives are described in the sections below.

4.3.1 Start-activity

primitive

(start-activity <resource> <activity-type> [:duration <time>] [<param-val-pair>])*

The start-activity primitive is used to initiate action in a module external to the action selection architecture. Like all primitive tasks, a start-activity task takes zero time to execute and is terminated immediately[10]. However, an activity started by the primitive will typically go on for some non-zero time interval. To allow PDL to influence the activity during this interval and to respond when it completes, the start-activity returns a pointer to a representation of the activity. For example, the start-activity step in the following procedure signals a resource module (either left-hand or right-hand) to begin an activity of type *pressing*. A representation of the activity is returned when step *s1* terminates and is bound to the variable *?a*. The activity's completion is later (1 second later) signaled by a cogevent of the form *(completed <activity>)* which, in this case, results in the termination of the overall task.

[10] The term "task" is reserved for actions and potential actions represented within the action selection architecture. "Activities" are performed outside the architecture.

```
(procedure
  (index (press button ?b with ?hand))
  (profile ?hand)
  (step s1 (start-activity ?hand pressing :target ?b :duration (1 second) => ?a))
  (step s2 (terminate) (waitfor (completed ?a))))
```

A start-activity task essentially sends a message to a resource[11] module to begin doing something. A start-activity step must specify the resource that will receive the message followed by the type of activity to be initiated. Other parameters may then be specified including :*duration* and others specific to the activity type (e.g. *pressing* activities require a :*target*). If no duration parameter is specified in PDL, duration is determined by the resource module and/or the activity type definition.

4.3.2 Terminate

primitive

(terminate [<task>] [>> <return-value>])

A terminate step defines conditions for stopping execution of a specified task should stop. By default, the target task is the one whose associated procedure contains the terminate step. Optionally, the step can specify some other task to be terminated. For example, the procedure below specifies that the agent should whistle while it works, but stop whistling if it gets chapped lips. The gold mining task, parent of the tasks generated from steps of the procedure, terminates when the work is done.

```
(procedure
  (index (mine gold))
  (step s1 (whistle))
  (step s2 (work))
  (step s3 (terminate ?s1) (waitfor (chapped lips)))
  (step s4 (terminate) (waitfor ?s2)))
```

Terminating a task has a number of effects:

- the task's state is set to *terminated*
- the task is removed from the action selection architecture's agenda
- the architecture stop monitoring waitfor preconditions associated with the task
- a cogevent of the form *(terminated <task>)* is generated – see section 4.2.4
- any resources allocated to the task are deallocated
- All of its subtasks are themselves terminated (indirect termination)
- If it is a periodic task (4.2.6) that passes its recurrence test and was not indirectly terminated, the task is restarted

[11] Only resources represented by a module external to the action selection architecture, and thus a component of the agents resource architecture, can receive start-activity messages. Resources named in profile clauses but not externally represented can still be the subject of allocation decisions. These are "virtual resources."

4.3.3 Reset

primitive

(reset <task>)

Reset causes the target task to terminate and then restart with all preconditions satisfied. It is generally used for trying again after failure. E.g.

```
(procedure
  (index (start-engine))
  (step s1 (turn-key))
  (step s2 (reset) (waitfor (engine-sound sputtering)))
  (step s3 (terminate) (waitfor (engine-sound turned-over))))
```

4.3.4 Cogevent

primitive

(cogevent <event>)

The cogevent primitive generates a cogevent of the specified form, potentially matching task preconditions just as cogevents generated by resources (especially perceptual resources) or by the action selection architecture. One important use of this primitive is to represents states that are inferred but not directly observed, such as hidden effects of an agent action. For example, step s4 generates an event representing the inference that an elevator has been summoned after pressing a button for this purpose.

```
(step s3 (press button elevator-down-button) ..)
(step s4 (cogvent (summoned elevator)) (waitfor ?s3))
```

The <event> parameter of a cogevent step can be any parenthesized expression not containing variables.

4.3.5 Reprioritize

primitive

(reprioritize [<task>])

Reprioritize steps are used to specify conditions in which task priorities might have changed; justifying reevaluation of resource allocation decisions. A reprioritize action causes the architecture to recompute the specified task's priority, then initiate a general competition for the resource(s) needed by the task. If the task is enabled but has not been allocated resources, this may result in immediate interruption of the task currently using

those resources. If the task is currently ongoing, reprioritization may cause it to be interrupted.

4.3.6 Hold-resource

primitive

(hold-resource <resource-name> [:ancestor <integer>])

Hold resource adds a resource to the list of resources a task needs in order to execute and then causes the task to compete for the resource with other contenders. Whereas the profile clause (4.2.8) establishes resource requirements as the task is enabled and its procedure selected, hold-resource adds requirements while the task is already ongoing. If the task competes successfully, there is no immediate effect. If some other task requiring the specified resource has higher priority, the task is interrupted.

The optional ancestor parameter specifies the target task. By default, the new requirement is added to the parent of the hold-resource task – i.e. the task whose associated procedure contains the hold-resource step. This corresponds to an ancestor value of 1 (1 level up the task hierarchy). Higher values target tasks higher in the hierarchy.

4.3.7 Release-resource

primitive

(release-resource <resource-name> [:ancestor <integer>])

Release-resource removes a resource from the list of resources a specified task requires in order to execute, and then causes the task to compete for its needed resources. It is typically invoked while the task is ongoing, freeing up the resource for use by some other task. The optional ancestor parameter specifies the target task. By default, the resource requirement is subtracted from the parent of the release-resource task – i.e. the task whose associated procedure contains the release-resource step. This corresponds to an ancestor value of 1 (1 level up the task hierarchy). Higher values target tasks higher in the hierarchy.

4.4 PDL variables

An understanding of how variable binding occurs and where the information comes from is crucial for specifying behavior in PDL. Variables in PDL become bound (and rebound) to values in several different circumstances as summarized below:

- variables in an index clause are bound after procedure selection
- variables in a profile clause are bound after procedure selection
- step tags are turned into variables and bound to tasks during task refinement

- variables in waitfor clauses are bound when matching cogevents occur
- variables in a selection clause are bound just prior to procedure selection
- variables in a return value form (following a =>) are bound at task termination
- the map variable in a forall clause is bound during task refinement
- global variables are initially bound as the agent is initialized

Apex maintains two kinds of variables: local and global. Local variables are defined with respect to a set of sibling tasks – i.e. immediate subtasks of a common parent. For example, the task *{task-25 (get milk from refrigerator fridge-1 with right-hand)}* might become enabled and the following procedure selected to carry it out:

```
(procedure
  (index (get ?item-type from refrigerator ?refrigerator with ?hand))
  (profile ?hand)
  (step s1 (open door of ?refrigerator with ?speed)
        (select ?speed (if (> (hunger ?agent) 5) 'quickly 'slowly)))
  (step s2 (find ?item-type in ?refrigerator => ?location) (waitfor ?s1))
  (step s3 (grasp object at ?location with ?hand) (waitfor ?s2))
  (step s4 (remove hand ?hand from ?refrigerator) (waitfor (grasped ?item)))
  (step s5 (close door of ?refrigerator) (waitfor ?s4))
  (step s6 (terminate) (waitfor ?s5)))
```

In selecting the procedure, the variables *?item-type*, *?refrigerator* and *?hand* become bound to the values *milk*, *fridge-1* and *right-hand* respectively. Later, when *task-25* is allocated the *right-hand* resource, new tasks will be created including, e.g.

```
{task-28 (open door of refrigerator-1 with ?speed)}
{task-32 (close door of refrigerator-1)}
```

Together these local variable bindings generated by selecting a procedure for task-25 form the **local context** for these tasks. The local context is stored with the parent task. Note that the printed form of these tasks has some variables replaced by values and some as variables. The writing convention is that values are shown instead of variables if bindings have been established. Just after task refinement, the variable ?refrigerator is bound but ?speed is not. This convention does not imply that these values are fixed for the lifetime of the task. Generally, if a binding changes, the task description will change to reflect this. Tasks are stored with variables unbound; replacement occurs as needed based on the current local context.

When the task refinement process creates new subtasks, new bindings are added to the local context. First, a new variable is created for each step tag in the selected procedure. For instance, the variable *?s5* is created and bound to *task-32*; the binding is then added to the local context stored with *task-25*. Second, the variable *?self* is created and bound to *task-25*, enabling subtasks of *task-25* to refer to their parent.

Following task refinement, the state of each task is established. Tasks with waitfor preconditions are initialized in the *pending* state and must await enabling cogevents. Tasks such as *task-28* have no preconditions and thus start in an *enabled*

state. Before procedure-selection for this task is performed, its select clause is evaluated. In this case, the variable *?speed* will either be assigned the value *slowly* or *quickly* depending on the hunger value of the agent. This new variable binding will then be added to the local context, making it available to specify *task-28* and any of its siblings.

With the value of ?speed defined, *task-28* becomes fully specified[12]. A procedure for it is selected, it is executed in the usual fashion and later terminates, enabling *task-29* for finding milk in *fridge-1*. The termination of *task-29* has an important side-effect. It returns a value which is bound to the variable ?location. The binding is added to the local context.

Bindings are frequently generated as cogevents match to preconditions expressed in a waitfor clause. In this case, it is assumed that a hand resource automatically generated an event of the form *(grasped <object>)* whenever it succeeds in a grasp action. In this case, the hand generates *(grasped milk-1)* which causes the variable ?item to become bound to *milk-1*. This binding is then added to the local context.

Global variables are initially defined when the agent is initialized. The only global variable of general importance is *?agent* which is always bound to a representation of the intelligent agent as a whole (although see 4.2.11). To use this effectively requires knowledge of the kinds of state information stored in an agent structure and how to access them (6.5). The example used above in which the hunger value of the agent is accessed is fanciful, though it is possible to extend the general agent model to include any kind of state data.

Information that results in variable bindings comes from several places. First, it can come from processes internal to the action selection architecture itself. For example, the architecture creates the tasks that get bound to step variables and generates cogevents signaling, e.g. task termination, task interruption and resource allocation (appendix A). Second, resources generate cogevents describing the internal state of those resources and, in the case of perceptual resources, external events and states. Finally, the action selection architecture can in principle retrieve information from a memory component. The action selection architecture does not include a memory element, although see Freed (1998) for an example.

[12] All the variables in a task description must be specified prior to selecting a procedure – i.e. all must be assigned values either before the task becomes enabled, during enablement as a consequence of cogevent matches, or during the procedure selection process by a select clause. If procedure selection is attempted for a task that has not been fully specified, this produces an error.

References

Freed, M. (2000) Reactive Prioritization. *Proceedings 2nd NASA International Workshop on Planning and Scheduling for Space*. San Francisco, CA.

Freed, M. (1998a) Simulating Human Behavior in Complex, Dynamic Environments. Doctoral Dissertation. Department of Computer Science, Northwestern University.

Freed, M. (1998b) Managing multiple tasks in complex, dynamic environments. In *Proceedings of the 1998 National Conference on Artificial Intelligence*. Madison, Wisconsin.

Freed, Michael and Remington, R. (2000a) GOMS, GOMS+ and PDL. In *Working Notes of the AAAI Fall Symposium on Simulating Human Agents*. Falmouth, Massachusetts.

Freed, M. and Remington, R. (2000b) Making Human-Machine System Simulation a Practical Engineering Tool: An APEX Overview. In *Proceedings of the 2000 International Conference on Cognitive Modeling*. Groningen, Holland.

Freed, M. and Remington, R. (1998) A conceptual framework for predicting errors in complex human-machine environments. In *Proceedings of the 1998 Meeting of The Cognitive Science Society.* Madison, Wisconsin.

Freed, M. and Remington, R. (1997*)* Managing decision resources in plan execution. *Proceedings of the Fifteenth International Joint Conference on Artificial Intelligence*. Nagoya, Japan.

Freed, M. and Shafto, M. (1997) Human System Modeling: Some Principles and a Pragmatic Approach. *Proceedings of the 4th International Workshop on the Design, Specification, and Verification of Interactive Systems*. Granada, Spain.

Freed, M., Shafto, M., and Remington, R. (1998) Using simulation to evaluate designs: The APEX approach. In Chatty, S. and Dewan, P., editors, *Engineering for Human-Computer Interaction*, chapter 12. Kluwer Academic

John, B. E., Vera, A. H., Matessa, M., Freed, M., and Remington, R. (2002) Automating CPM-GOMS. In *Proceedings of CHI'02: Conference on Human Factors in Computing Systems.* ACM, New York, pp. 147-154.

Appendix A: Event Traces

A.1 Predefined show-levels

all	: all events
none	: no events
default	: only task-started events
actions	: resource related events
asa-low	: action selection architecture event, low detail
asa-medium	: action selection architecture event, medium detail
asa-high	: action selection architecture event, high detail
cogevents	: cognitive events
simulation	: activity related events

A.2 Lisp commands for controlling trace output

(show)	: query the current TraceConstraint (syntax on next page)
(show :runtime)	: see event trace as simulation runs (useful for debugging)
(show :hms)	: see time displayed in hours/mins/secs
*(*show :level *level)*	: effects the given ShowLevel (see list of levels below)
*(*show *EventType)*	: adds event type to trace (see event types list)
(show Constraint)	: adds events matching given TraceConstraint to trace
(unshow)	: turns off event trace
(unshow :runtime)	: suppress runtime display of event trace
(unshow :hms)	: see time displayed as an integer
*(*unshow *EventType)*	: removes event type from trace (see event types lists below)
(unshow Constraint)	: removes events matching given TraceConstraint from trace
(generate-trace)	: generate and print the trace
(trace-size)	: query number of events in latest trace

(define-show-level *name TraceConstraint*) : defines show level (*name* is symbol)

A.3 Trace constraint syntax

TraceConstraint :
  TraceParameter { see below }
| (and TraceConstraint*) { matches events meeting all given constraints }
| (or TraceConstraint*) { matches events meeting any given constraint }
| (not TraceConstraint) { matches events that fail the given constraint }

TraceParameter :
  (event-type <symbol>) { matches events of given type }
| (object-id <symbol>) { matches events containing given object }
| (time-range (<low> <high>)) { matches events occuring in given time range }

TimeExpression : (TimePair+) { one or more int/unit pairs }

TimePair : (<integer> TimeUnit)
TimeUnit : ms | msec | msecs
| s | sec | secs | second | seconds
| m | min | mins | minute | minutes
| d | day | days

A.4 Event Types

Each event type is explicitly logged and can be filtered in/out for trace view. Verbose event descriptions name event parameters not including timestamp.

Action selection architecture events

Types in curly brackets refer to ASA actions that are not yet supported. Causal event 0 is the *initialize* event. * means an associated cogevent is generated. Terminology changes: *enabled* refers to satisfaction of non-resource preconditions – any resource preconditions not yet satisfied; *executed* tasks must take 0 time – i.e. primitive and special (Lisp callout) tasks; *started* is used for non-primitives. Resource deallocation events occur when a task is terminated or interrupted.

Need to review this list for meaningful and constent naming, completeness/usefulness of causal information.

	Event type	**Description (not incl time)**	**Causal events**
1	task-created	<task>	0,17
2	monitor-created	<monitor> <task>	0,17
3	monitor-satisfied	<monitor> <cogevent>	2+any
4	{monitor-tentatively-satisifed}	<monitor> <cogevent>	2+any
5	{monitor-expired}	<monitor>	2+time
6	{monitor-desatisfied}	<monitor> <cogevent>	2+any
7	enablement-testing-started	<task>	3
8	enabled*	<task>	1+7+3*
9	refused-enablement*	<task>	1+7
10	procedure-selected	<task> => <procedure>	8+10
11	conflict-detected	<task> <task> <resource>	10,12
12	conflict-resolved*	: winner <task> :loser <task>	11,13/13
13	priority-computed	for <task> = <priority>	11,15
14	resource-allocated*	<task> <resources>	11+12,16
15	interrupted*	<task> <task>	8+12
16	resource-deallocated*	<resource> :from <task>	15,20
17	task-started*	<task>	8+14
18	executed*	<task>	8+14
19	resumed*	<task>	15+14
20	terminated*	<task>	18,20
21	reset*	<task>	18

22	reinstantiated*	<task>	8,17,20
23	assumption-violated	<varname> <agent>	3

Resource architecure events

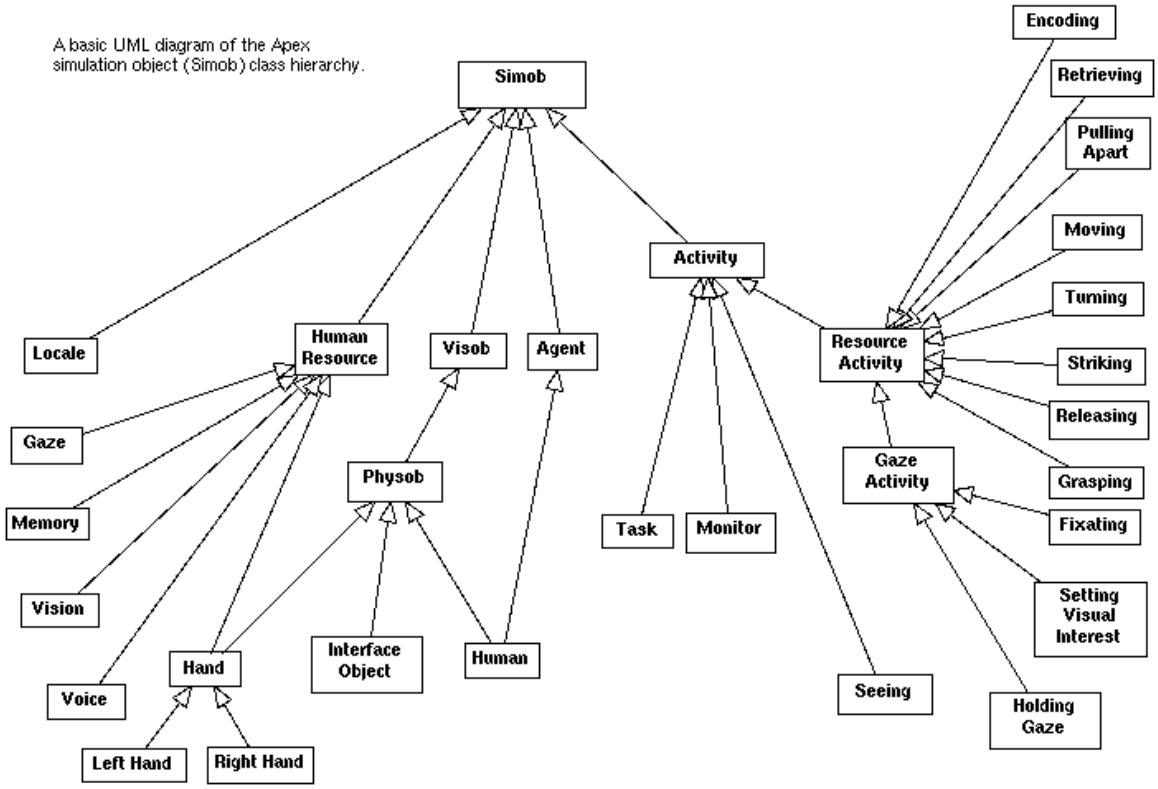
	Event-type	**Description (not incl. time)**	**Causals**
Control			
1	started*	<activity> <parameters>*	
2	completed*	<activity>	
3	stopped*	<activity>	
4	clobbered	<activity> :by <activity>	
Vision			
1	nothing-new*	vision	
2	pos*	<visobfile> <coordinates>	
3	color*	<visobfile> <colorname>	
4	orientation*	<visobfile> <degrees>	
5	shape*	<visobfile> <shapelist|shape>	
6	contrast*	<visobfile> <value>	
7	blink*	<visobfile> <rate>	
8	elements*	<visobfile> <list>	
9	contains*	<visobfile> <vof-list>	
10	contained-by*	<visobfile> <visobfile>	
Gaze			
1	fixated*	<visobfile>	
2	winnowed*	<visobfile> <feature>	
3	held-gaze*	<locus> <time>	
Memory			
1	encoded*	<proposition>	
2	retrieved*	<proposition>	
3	new*	<proposition>	
4	revalued*	<proposition>	
5	refreshed*	<proposition>	
6	refined*	<proposition>	
Hands			
1	grasped*	<hand> <object>	
2	released*	<hand> <object>	
3	moved*	<hand> <object>	
4	turned-dial*	<hand> <dial> <position>	
5	typed*	<hand> <keyboard> <msg>	

General simulation events

1	started-activity	<activity> <primary-simob>	
2	initialized-activity	<activity> <primary-simob>	

3	updated-activity	<activity> <primary-simob>	
4	stopped-activity	<activity> <primary-simob>	
5	completed-activity	<activity> <primary-simob>	

Appendix B: Native Object Hierarchy



Appendix C: Troubleshooting

C.1 Common problems

This section contain possible solutions to some of the problems users have reported.

Problem:
A task that should start never does. It seems to wait forever.

Explanations/Solutions:

1. There is a mismatch between the forms (patterns) of the event and waitfor precondition
    a. One of the patterns contains a spelling error
    b. There is a difference in the order of pattern elements. E.g. a perceptual event of the form (between a b c) won't match a precondition of the form (between a c b), even though both mean that a is observed to be between b and c.
    c. There is a difference in the type of pattern elements. E.g. (distance a b 2) vs. (distance a b 2.0)
    d. The number of parameters in the events and precondition are different.
2. The event occurs before the task whose precondition it should match comes into existence. This can happen when events and preconditions are both created at the same "instant" according to the simulation clock.
3. The event occurs after the task whose precondition it should match is (prematurely) terminated.

Problem:
A task starts prematurely, before its waitfor preconditions should be satisfied.

Explanations/solutions:

1. A precondition is less constrained than it seems to be, allowing it to match events that it shouldn't match. E.g. A procedure consists of steps s1 (no preconditions), s2 (waits for s1; binds?x when it terminates) and s3 (waits for (color ?x red)). The intention may be to determine an object of interest in step s2 and then wait for it to turn red, but here s3 will be enabled by observing ANY red object.
2. An event matching the precondition is being generated from an unexpected source
3. There are disjoint enablement conditions (multiple waitfor clauses), allowing the task to become enabled for execution in an unexpected way.

C.2 Known bugs

Note: bugs associated with specific Apex processes or PDL constructs are listed in the appropriate section.

Apex can crash if an agent acts in reference to a world object at time 0. The reason is that the behavior might be inititated before the world object is specified and incorporated into the physical environment model. Avoid this problem by insuring that the assemble method is called on all physical environment objects before any agent objects are initialized.

The read macro #L that forces a Lisp evaluation at create time does not work in primitive (directly executable) procedure steps.

Activities can be started with negative duration values. This should produce an error.

Appendix D: Pattern matching

Pattern matching is used in a variety of PDL constructs including index, waitfor and step. The following examples illustrate the behavior and capabilities of the pattern matching algorithm. This text and the algorithm itself are taken from *Paradigms of AI Programming* by Peter Norvig (1991).

```
(pat-match '(x = (?is ?n numberp)) '(x = 34))
;;;; -> ((?n . 34))

(pat-match '(x = (?is ?n numberp)) '(x = x))
;;;; -> NIL

(pat-match '(?x (?or < = >) ?y) '(3 < 4))
;;;; -> ((?Y . 4) (?X . 3))

(pat-match '(x = (?and (?is ?n numberp) (?is ?n oddp))) '(x = 3))
;;;; -> ((?N . 3))

(pat-match '(?x /= (?not ?x)) '(3 /= 4))
;;;; -> ((?X . 3))

(pat-match '(?x > ?y (?if (> ?x ?y))) '(4 > 3))
;;;; -> ((?Y . 3) (?X . 4))

(pat-match '(a (?* ?x) d) '(a b c d))
;;;; -> ((?X B C))

(pat-match '(a (?* ?x) (?* ?y) d) '(a b c d))
;;;; -> ((?Y B C) (?X))

(pat-match '(a (?* ?x) (?* ?y) ?x ?y) '(a b c d (b c) (d)))
;;;; -> ((?Y D) (?X B C))

(pat-match '(?x ?op ?y is ?z (?if (eql (?op ?x ?y) ?z))) '(3 + 4 is 7))
;;;; -> ((?Z . 7) (?Y . 4) (?OP . +) (?X . 3))

(pat-match '(?x ?op ?y (?if (?op ?x ?y))) '(3 > 4))
;;;; -> NIL

(pat-match-abbrev '?x* '(?* ?x))
;;;; -> (?* ?X)

(pat-match-abbrev '?y* '(?* ?y))
;;;; -> (?* ?Y)
```

```
(setf axyd (expand-pat-match-abbrev '(a ?x* ?y* d)))
;;;; -> (A (?* ?X) (?* ?Y) D)

(pat-match axyd '(a b c d))
;;;; -> ((?Y B C) (?X))

(pat-match '(((?* ?x) (?* ?y)) ?x ?y) '((a b c d) (a b) (c d)))
;;;; -> NIL
```